A NOVEL APPROACH TO PLANETARY PRECISION LANDING USING PARAFOILS

Final Report

JPL Task 961

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A. OBJECTIVES

In this research, we have addressed the problem of how to achieve precision landing, in an autonomous manner, through an actively-controlled parafoil. By precision landing, we mean the capability of steering the vehicle to a pre-specified target area on the ground. The mechanization to achieve this maneuverability is provided by a parafoil, i.e. a high-glide parachute characterized by airfoil-type canopy cross-sections and wing-type plan forms, which can actively be steered to control the trajectory. Previous flight tests done at NASA Dryden (1991-1996) have established the feasibility of autonomous precision landing on Earth by means of GPS and a commercially-available ram-air parachute. This research leverages on this past achievement, and addresses the fundamental issues involved in using an actively-controlled parafoil and an image-in-the-loop architecture to land the spacecraft on a specific planetary surface location.

The objectives of the task were:

1) To obtain a detailed model of the parafoil dynamics and of the system dynamics in terminal descent.
2) To obtain sensor/actuator models ready to be used in control design.
3) To synthesize a feedback/switching controller showing some robustness to lateral wind gusts and enabling landing on the target with high precision.
4) To demonstrate the concept by simulation.

However, during the course of the investigation, we realized that it would have been more appropriate to look at the fundamental issues rather than focusing on a point design problem. Therefore, based on the fact that a parafoil-assisted descent needs first to come to terms with an unknown atmosphere, we focused our work on developing an atmospheric density estimator.

B. PROGRESS AND RESULTS

Significant progress has been made on achieving the first and second objectives. We now have a working dynamic model (Fig. 1 and Fig. 2) for simulations of the probe/parafoil system during descent in wind. Models of Mars' atmosphere used for the PathFinder and MER simulations have been used, as well as simpler models derived for our balloon modeling work in the Mars Aerobot Validation Program for Earth, Venus, and Titan. The dynamic model of the system includes a rigid body model of the probe/parafoil vehicle in a flat Earth/planet approximation, a model of the apparent mass forces and torques acting on the inflated parafoil (which is a predominant effect in parafoil dynamics), a model of the aerodynamic coefficients of the canopy, the suspension lines, and load as well. The aerodynamic coefficients of the parafoil are those of a typical sports jumper application [Ref. 1].

A sensor suite is also modeled, and consists of an accelerometer, a star tracker, and a three-axis gyro mounted on the body of the probe. A more complex model has also been developed which also features a gimbaled camera mounted on the probe, actuated via a two-axis gimbal. The pulley-actuator model is represented by a first-order process, which takes into account the symmetric and asymmetric line pull with some characteristic lag. The dynamic model is of sufficient generality as to accommodate other prospective devices for controlled planetary descent, namely rotafoils, or Stokes decelerators, provided their aerodynamic characteristics are known in the form of wind-tunnel-derived aerodynamic coefficients. Figure 1 shows the initial geometry of the system, as well as a typical descent profile with maneuvers such as: pull lines symmetrically to achieve a sink rate, operate a turn to the right (or to the left) via an asymmetric pull of the lines, and finally perform a flare to touch-down in proximity of the target. Figure 2 shows the elements present in the model and some details of the simulation environment, and Figure 3 (left) shows the profile of lift-to-drag ratio required to perform the maneuvers of Figure 1, as well as (right) the discrepancy in descent trajectory when a 3m/s lateral wind acts steadily during the descent. This simulation shows the dramatic effect that wind can have, and hints at the appropriate control philosophy that is required, which will be the subject of future work.

Figure 4 (left) shows the excellent performance of the on-board, discrete-time, model-based, density estimator, which relies on body-fixed accelerometer measurements only. The filter state equation is $\dot{r} = -b h r$ where ρ is the current density, β the height scale factor, and h the current height along the local vertical, and the measurement equation is given by $y = Hx + M^{-1}C_0$ where H is the measurement sensitivity matrix, M is the mass matrix, and C_0 the density-independent part of the equations of motion (of the form $M\ddot{q} = C_0 + rC_1$). We assume that the knowledge of the aerodynamic and geometric parameters is exact, although methods for their estimation are available. Figure 4 (right) depicts the functional phase of the descent to be considered in a more thorough study. The envisioned control architecture is based on an optical guidance scheme [Ref. 2]. The essentials of this architecture rely on a measure of the coordinates on the planetary geoid where the landing site is located. These coordinates are given in terms of longitude, latitude, and planetocentric radius. More simply, with the flat planet model we have developed, they are given in terms of (x,y,z) inertial coordinates. The control logic includes a feedback architecture to compensate for deviations from the intended flight path originated by wind gusts, a feed-forward logic which generates the programmed descent path and provides a reference for the feedback controller, and a switching logic to enable/disable the precision landing architecture when the system is in proximity of the target.

C. SIGNIFICANCE OF RESULTS

This task developed a dynamic-aerodynamic-control-estimation model of a fully-actuated parafoil controlling the descent of a space probe in a Mars-like planetary atmosphere. Based on the promising results allowed by the model developed in this task, our future work will focus on more robust estimation and control schemes, which will guide the vehicle to land autonomously at a specified target point. The findings from this investigation will apply to missions to Mars, Titan, and other planets with an atmosphere. The preliminary results obtained so far indicate that precision control of these types of vehicles can be achieved, provided that enough control authority and enough knowledge of the atmospheric parameters (density, wind magnitude and direction) are available.

D. FINANCIAL STATUS

The total funding for this task was $81,000, of which $71,000 was expended.

E. PERSONNEL

No other personnel were involved.

F. PUBLICATIONS

[1] M. B. Quadrelli, J. M. Cameron, V. V. Kerzhanovic, "Modeling, Simulation, and Control of Parachute/Balloon Flight Systems for Mars Exploration," presented as paper 2001-2026 at the 16th AIAA Aerodynamic Decelerator Systems Technology Conference 21-24 May 2001, in Boston, MA, also submitted for publication to the Journal of Guidance, Control, and Dynamics.

[2] A Microsoft PowerPoint presentation entitled "A Novel Approach to Planetary Precision Landing Using Parafoils" has been distributed to the participants of the EDL Workshop in the Embassy Suites, Arcadia, on March 26, 2002.

[2] Three papers derived from this DRDF work: "Precision Landing with Parafoils: Dynamics and Control," "Precision Landing with Parafoils: Atmospheric Density Estimation," and "Precision Landing with Parafoils: Wind Estimation" are in preparation.

[3] A proposal entitled "Robust Reentry Aeromaneuvering with Actively Controlled Ballutes," extending our idea into the hypersonic, rarefied flow regime, has been submitted to the FY'03 RTD call for proposals.

[4] A proposal entitled "Ribbon Assisted Lift/Drag Modulation and Heat Mitigation during Hypersonic Reentry," also extending our idea into the hypersonic, rarefied flow regime, has been submitted to the FY'03 DRDF.

G. REFERENCES

[1] W. Gockel, "Computer-Based Modeling and Analysis of a Parafoil-Load Vehicle," 14th AIAA Aerodynamic Decelerator Systems Technology Seminar, San Francisco, June 1997.

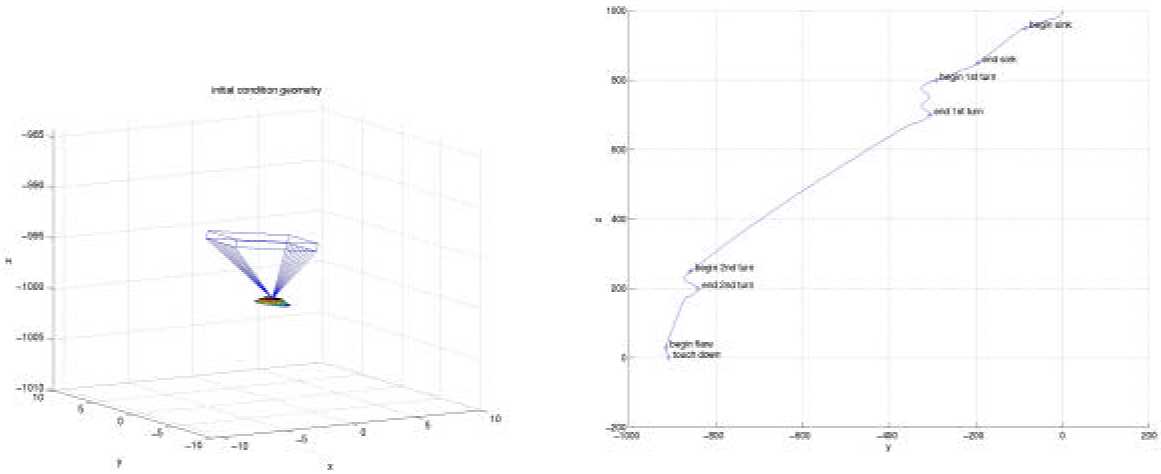

Figure 1. Geometry of problem (Left). The typical phases of a reentry trajectory (Right).

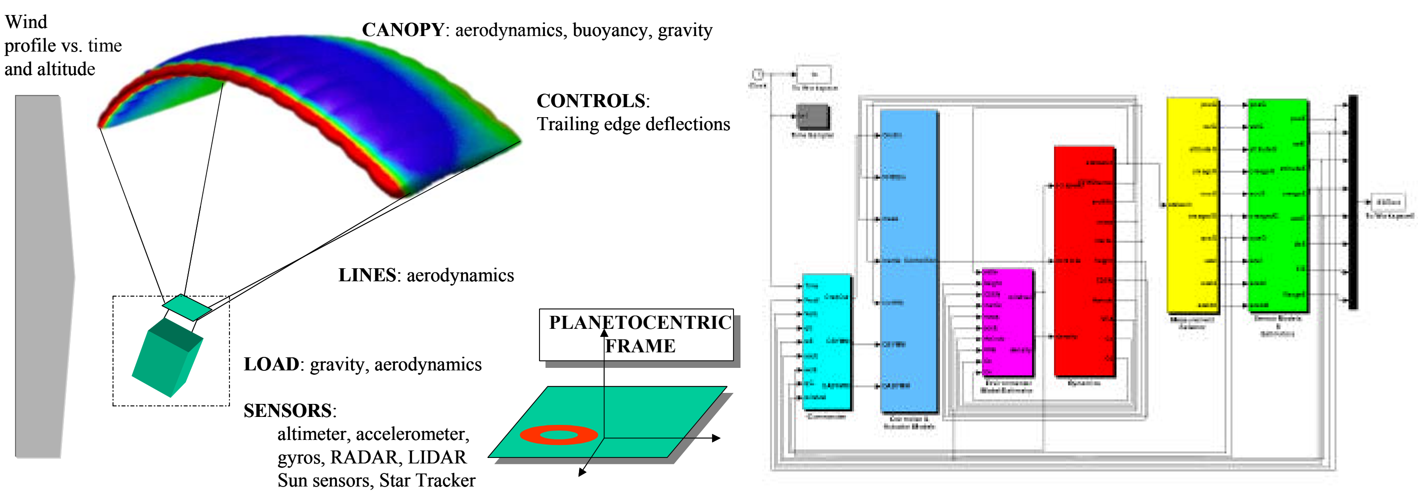

Figure 2. Details of the dynamics model (Left). Matlab/Simulink simulation model (Right).

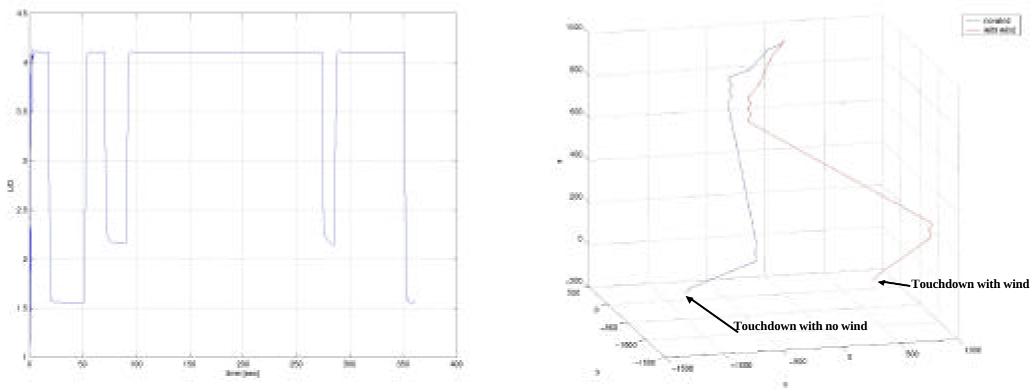

Figure 3. A typical lift-to-drag profile during descent (Left). Discrepancy in descent trajectories with and without wind (linear profile with altitude) present (Right).

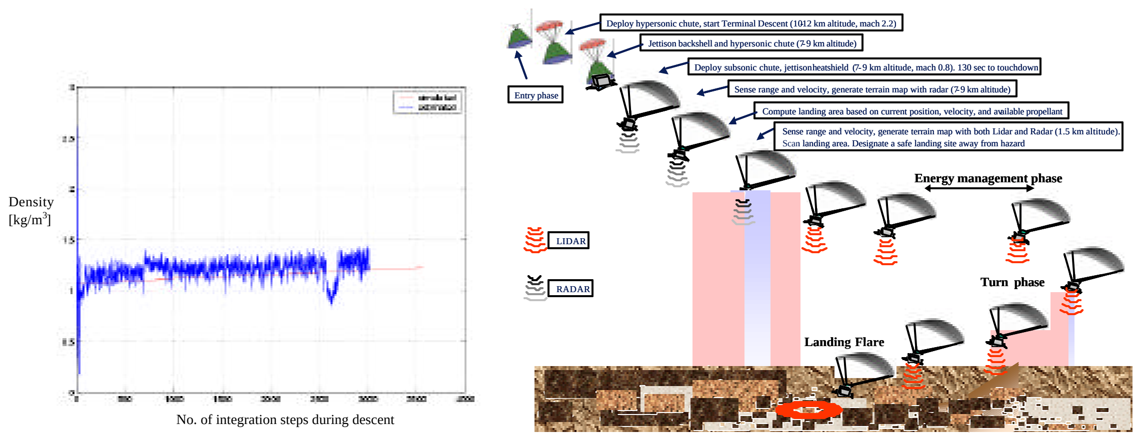

Figure 4. Simulated (red) vs. estimated (blue) density during descent (left). Functional description of parafoil-assisted descent phase (right).